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Review article

Heat Resistance in Liquids of *Enterococcus* spp., *Listeria* spp., *Escherichia coli, Yersinia enterocolitica, Salmonella* spp. and *Campylobacter* spp.

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Sörqvist S: Heat resistance in liquids of *Enterococcus* spp., *Listeria* spp., *Escherichia coli, Yersinia enterocolitica, Salmonella* spp. and *Campylobacter* spp. Acta vet. scand. 2003, 44, 1-19. – The aim of the work was to collect, evaluate, summarize and compare heat resistance data reported for *Campylobacter, Enterococcus, Escherichia, Listeria, Salmonella* and *Yersinia* spp. The work was limited to resistance in liquids with pH values 6-8. Results obtained under similar experimental conditions were sought. Thermal destruction lines for the various bacterial groups studied were constructed using $\log_{10} D$ values and treatment temperatures. There was a good linear relationship between $\log_{10} D$ and temperature with *Escherichia coli,* listerias and salmonellas. For campylobacters, enterococci and yersinias the relationships were weaker but, nevertheless, present. Using the slopes of the lines and their 95% confidence limits, *z* values and their 95% confidence limits were calculated. *z* values were compared with *z* values obtained from reports. The equations for the lines were also used for calculation of predicted means of *D* values at various treatment temperatures. 95% confidence limits on predicted means of *D* values and on predicted individual *D* values were also calculated. Lines and values are shown in figures and tables. Differences in heat resistance noted between and within the bacterial groups studied are discussed.

Campylobacter jejuni/coli; Enterococcus faecalis; Enterococcus faecium; Escherichia coli; Listeria innocua; Listeria ivanovii; Listeria monocytogenes; Listeria seeligeri; Listeria welshimeri; Salmonella; Yersinia enterocolitica; thermal resistance; influencing factors; methods of determination; differences between species; differences between strains.

Introduction

Microbiologists now and then need heat resistance data for various microorganisms. In the literature, data of this kind are frequently based on reports from few investigations. To collect the data required, however, may be a laborious and time-consuming task for the individual user. The literature is generally extensive and many factors that may have influenced the results reported must be taken into consideration (for general information on influencing factors, see e.g. *Hansen & Riemann* 1963, *Stumbo* 1973, *Pflug & Holcomb* 1983). Furthermore, the presentations of results often differ essentially.

The aim of the present work was to collect, summarize, evaluate and compare heat resistance data reported for *Campylobacter, Enterococcus, Escherichia, Listeria, Salmonella* and *Yersinia* spp. As it was well known that considerably more heat resistance results were published from investigations with liquids than from those with other heating menstrua, it was considered appropriate to base the work on results obtained in liquids. Moreover, results of this kind could be expected to reflect the inherent heat resistance of the bacteria investigated better than those obtained in more complex heating menstrua.

Reports published until 2000 were studied. Data produced under experimental conditions as similar as possible were sought. This meant that results from some kinds of experiments were excluded. The various types of excluded data are given below under the different subheadings in Experimental conditions. It should be mentioned here that extensive reviews of heat resistance data reported for *Escherichia coli* O157:H7, *Listeria monocytogenes* and *Salmonella* spp. have been published recently by *Stringer et al.* (2000), *Doyle et al.* (2001) and *Doyle & Mazzotta* (2000), respectively. However, the aims and the selections and analyses of data in these reviews differ from those in the present work.

Bacteria

The work deals with the following bacteria: *Campylobacter jejuni/coli, Enterococcus faecalis, Enterococcus faecium, Escherichia coli, Listeria innocua, Listeria ivanovii, Listeria monocytogenes, Listeria seeligeri, Listeria welshimeri, Salmonella* spp. and *Yersinia enterocolitica.* Some of these bacteria are well-known food-associated human pathogens, others are utilized - enterococci and *E. coli* - or proposed - *L. innocua* (*Foegeding & Stanley* 1991, *Fairchild & Foegeding* 1993) - as indicators. Some types of *E. coli* also appear as food-linked human pathogens (*Morgan et al.* 1988, *Murano & Pierson* 1992, 1993, *Clavero & Beuchat* 1995, *Clementi et al.* 1995, *Jackson et al.* 1996, *Blackburn et al.* 1997, *Williams & Ingham* 1997, *George & Peck* 1998, *Kaur et al.* 1998) and enterococci have recently emerged as one of the leading causes of nosocomial, non-food-associated, infections (*Kearns et al.* 1995).

Experimental conditions

Growth of test bacteria

In most cases the bacteria were grown in conventional media. In some investigations the growth media were milk, liquid egg products or clarified cabbage juice. The pH values of the media were given in some cases. The values varied from 5.6 to 7.4. Enterococci, *E. coli,* listerias and salmonellas were incubated aerobically at 30-37 °C and *Y. enterocolitica* aerobically at 25-37 °C. Campylobacters were grown microaerobically at 35-43 °C. In the great majority of cases the bacteria were incubated for 12-48 h, i.e. they could be considered to have reached the late logarithmic or stationary growth phase. At stationary growth phase, bacterial heat resistance is at a maximum (*Elliker & Frazier* 1938, *White* 1953, *Krishna Iyengar et al.* 1957, *Lemcke & White* 1959, *Beuchat & Lechowich* 1968, *Ng et al.* 1969, *Humphrey et al.* 1990, *Jackson et al.* 1996, *Lou & Yousef* 1996, *Kaur et al.* 1998, *Pagán et al.* 1998, 1999).

Heat resistance results obtained for bacteria grown under carbon, glucose or nitrogen starvation or other stress conditions (see e.g. *Ng et al.* 1969, *Jenkins et al.* 1988, *Lou & Yousef* 1996) were not used in the present work.

Conditions between growth and heat treatment

Results recorded for bacteria subjected to stress conditions prior to heat treatment were not used: sublethal heat shock (see e.g. *Mackey & Derrick* 1986, 1987b, 1990, *Bunning et al.*

1990, 1992, *Murano & Pierson* 1992, 1993, *Boutibonnes et al.* 1993, *Humphrey et al.* 1993a, *Flahaut et al.* 1996, 1997, *Shenoy & Murano* 1996, alkaline stress (*Humphrey et al.* 1991, 1993b), acid stress (*Farber & Pagotto* 1992, *Leyer & Johnson* 1993, *Williams & Ingham* 1998), osmotic stress (*Jørgensen et al.* 1995) or other types of stress (see e.g. *Boutibonnes et al.* 1993, *Flahaut et al.* 1996, 1997).

Heating menstrua

Heating menstrua used were milk and liquid milk products, broths, physiological saline and other salt solutions, liquid egg products, diluted soups, scalding waters used at chicken or pig slaughter, and some other liquids. Heat resistance results obtained in menstrua with pH values of approx. 6-8 were used in the present work, as the bacterial species investigated are known to have their maximum heat resistances in this pH range (see e.g. *Anellis et al.* 1954, *Krishna Iyengar et al.* 1957, *White* 1963, *Garibaldi et al.* 1969a, *Humphrey et al.* 1981, *Sanz Pérez et al.* 1982, *Okrend et al.* 1986, *Blackburn et al.* 1997, *Pagán et al.* 1998, 1999).
Results from experiments where salts, fats, carbohydrates, proteins or other substances were added to the heating menstrua with the aim of influencing the heat resistance of the test bacteria were excluded (see e.g. *Lategan & Vaughn* 1964, *Calhoun & Frazier* 1966, *Baird-Parker et al.* 1970, *Goepfert et al.* 1970, *Vrchlabski & Leistner* 1970, *Corry* 1974, *Anderson et al.* 1991, *Palumbo et al.* 1995, *Blackburn et al.* 1997, *Knight et al.* 1999).

Heat treatment

Various methods of heat treatment were applied, e.g. heating in water baths using glass capillary tubes, sealed glass tubes, glass ampoules or polythene pouches completely immersed in the water, test tubes placed with the water level to the bases of the test tube plugs, flasks or cups placed with the menstruum levels under the water level and in some cases shaken, and heating using pasteurizers, two-phase slug flow heat exchangers (*Bradshaw et al.* 1985, *Bunning et al.* 1986, 1988, 1992, *Konvincic et al.* 1991, *Clementi et al.* 1995), submerged-coil heating apparatuses (*Anderson et al.* 1991, *Jørgensen et al.* 1995, 1996, *Blackburn et al.* 1997, *Juneja et al.* 1998), thermoresistometers (*Read et al.* 1968, *Pagán et al.* 1998, 1999) and an "attemperated dilution blank method" (*Magnus et al.* 1986, 1988).
Results from experiments using rising heating temperatures (*Tsuchido et al.* 1974, *Mackey & Derrick* 1987a, *Quintavalla et al.* 1988, *Stephens et al.* 1994) were excluded.

Recovery of heat-treated bacteria

In the great majority of cases the recovery of heat-treated bacteria was performed on agar plates. Enterococci and *E. coli* were incubated aerobically at 30-37 °C for 24 h-7 days, listerias, salmonellas and *Y. enterocolitica* aerobically at 25-37 °C for 24 h-7 days and campylobacters microaerobically at 37-43 °C for 24-72 h. In some studies anaerobic recovery was used: *L. monocytogenes* (*Knabel et al.* 1990, *George et al.* 1998), *E. coli* (*Murano & Pierson* 1992, 1993, *Gadzella & Ingham* 1994, *Blackburn et al.* 1997, *George et al.* 1998, *George & Peck* 1998) and salmonellas (*Xavier & Ingham* 1993, *Blackburn et al.* 1997, *George et al.* 1998). Most Probable Number (MPN) techniques were applied in some investigations.
Procedures for repair of heat-injured bacteria were studied by *Ahmad et al.* (1978), *Northolt et al.* (1988), *Meyer & Donnelly* (1992), *Sörqvist* (1993, 1994) and *George et al.* (1998).
Results from experiments where heat-treated bacteria were recovered on selective or other media known to inhibit growth of heat-injured cells were excluded.

Table 1. *z* values reported from investigations where the experimental conditions laid down in this study were fulfilled.

Bacterium/ Bacterial group	z* values (°C) Range	Mean ± SD	No. of values	References
Enterococcus faecium	3.63-12.82	8.4 ± 2.5	14	*Sanz Pérez et al.* (1982), *Magnus et al.* (1986), *Quintavalla et al.* (1988), *Gordon & Ahmad* (1991), *Simpson et al.* (1994), *Mulak et al.* (1995)
Enterococcus faecalis	2.24-9.06	6.0 ± 2.5	10	*Gardner & Patton* (1975), *Sanz Pérez et al.* (1982), *Magnus et al.* (1986), *Quintavalla et al.* (1988)
Listeria innocua	4.65-6.9	5.8 ± 0.8	8	*Quintavalla & Barbuti* (1989), *Foegeding & Stanley* (1991), *Fairchild & Foegeding* (1993), *Palumbo et al.* (1995)
Listeria monocytogenes	4.30-11.45	6.1 ± 1.2	85	*Bradshaw et al.* (1985, 1987b, 1991), *Beuchat et al.* (1986), *Bunning et al.* (1986, 1988), *Donnelly & Briggs* (1986), *El-Shenawy et al.* (1989), *Lemaire et al.* (1989), *Quintavalla & Barbuti* (1989), *Foegeding & Leasor* (1990), *Linton et al.* (1990), *Foegeding & Stanley* (1991), *Quintavalla & Campanini* (1991), *Fairchild & Foegeding* (1993), *Sörqvist* (1993, 1994), *Bartlett & Hawke* (1995), *Palumbo et al.* (1995), *Muriana et al.* (1996), *Schuman & Sheldon* (1997), *Casadei et al.* (1998), *Pagán et al.* (1998), *Rowan & Anderson* (1998), *Knight et al.* (1999)
Listeria ivanovii	6.3-6.6	6.5 ± 0.2	2	*Bradshaw et al.* (1991)
Listeria seeligeri	6.4-6.9	6.7 ± 0.3	2	*Bradshaw et al.* (1991)
Listeria welshimeri	6.1-6.9	6.5 ± 0.5	2	*Bradshaw et al.* (1991)
Escherichia coli	3.4-6.0	5.1 ± 0.8	11	*Read et al.* (1961), *Dega et al.* (1972), *Morgan et al.* (1988), *Clementi et al.* (1995), *Blackburn et al.* (1997), *Williams & Ingham* (1998)
Yersinia enterocolitica	4.0-5.78	4.8 ± 0.6	10	*Lovett et al.* (1982), *Sörqvist* (1989), *Sörqvist & Danielsson-Tham* (1990), *Pagán et al.* (1999)
Salmonella spp. (except *Salm. senftenberg* 775W)	3.24-9.5	5.5 ± 1.7	36	*Anellis et al.* (1954), *Garibaldi et al.* (1969b), *Dega et al.* (1972), *Gibson* (1973), *Bradshaw et al.* (1987a), *Sörqvist & Danielsson-Tham* (1990), *Shah et al.* (1991), *Xavier & Ingham* (1993), *Wolfson & Sumner* (1994) *Palumbo et al.* (1995), *Blackburn et al.* (1997), *Schuman & Sheldon* (1997), *Humpheson et al.* (1998), *Michalski et al.* (1999)
Salm. senftenberg 775W	5.3-6.8	6.0 ± 0.4	13	*Anellis et al.* (1954), *Thomas et al.* (1966), *Baird-Parker* et al. (1970), Gibson (1973)
Campylobacter jejuni/coli	2.8-5.81	4.8 ± 0.7	14	*Blankenship & Craven* (1982), *Waterman* (1982), *Sörqvist* (1989), *Sörqvist & Danielsson-Tham* (1990)

* The *z* value is the number of degrees of temperature change needed to change the *D* value by a factor of 10 (The term *D* value, see Table 3).

Table 2. *z* values obtained using the slopes of thermal destruction lines constructed in the study and their 95% confidence limits and, for comparison, summaries of reported and calculated *z* values.

Bacterium/ Bacterial group	*z* values (°C)* Obtained value and its 95% confidence interval	Reported and calculated** values Range	Mean ± SD	No. of values
Enterococcus faecium	9.6 (8.8 - 10.5)	3.63 - 14.3	10.2 ± 3.3	24
Enterococcus faecalis	9.5 (8.5 - 10.8)	2.24 - 14.2	8.1 ± 3.2	36
Listeria innocua	5.0 (4.5 - 5.6)	4.65 - 7.3	6.0 ± 0.9	9
Listeria monocytogenes	5.7 (5.6 - 5.9)	4.30 - 11.45	6.3 ± 1.3	103
Listeria ivanovii, L.seeligeri, L. welshimeri †	6.4 (6.1 - 6.7)	6.1 - 6.9	6.5 ± 0.3	6
Escherichia coli	6.0 (5.9 - 6.1)	3.2 - 9.1	5.4 ± 1.5	33
Yersinia enterocolitica	6.7 (6.0 - 7.7)	4.0 - 13.7	6.6 ± 2.7	20
Salmonella spp. (except *Salm. senftenberg* 775W)	5.2 (5.1 - 5.3)	3.24 - 9.5	5.1 ± 1.6	63
Salmonella senftenberg 775W	5.8 (5.4 - 6.4)	4.5 - 9.1	6.2 ± 1.1	16
Campylobacter jejuni/coli	6.4 (5.8 - 7.0)	2.8 - 8.0	5.5 ± 1.1	24

** Calculated *z* values were figured out from reported or calculated *D* values (see Types of collected data and statistical analysis) and reported treatment temperatures.
† *Listeria ivanovii, L. seeligeri* and *L. welshimeri* are taken together.

Types of collected data and statistical analysis

D and *z* values were collected from the studied literature. The *D* value is the time of heat treatment required at a certain temperature to destroy 90% of the bacterial cells, and the *z* value is the number of degrees of temperature change needed to change the *D* value by a factor of 10 (*Stumbo* 1973). When not reported, *D* values were, where possible, calculated from bacterial counts and periods of time of heat treatment given in texts, tables or figures. Some *z* values were worked out from reported or calculated *D* values and reported treatment temperatures.

For each of the bacterial species/groups studied, the $\log_{10}$ of *D* values recorded were plotted *vs* temperature and a thermal destruction line (*Stumbo* 1973) was fitted using the method of least squares (*Colton* 1974). The equation for the line is $\log_{10} D = a - bt$, where *D* is the decimal reduction time in s, *a* the intercept, *-b* the slope and *t* the treatment temperature in °C. The degree of linear relationship between the temperatures used and the logarithms of *D* values recorded was expressed by the coefficient of correlation, *r* (*Colton* 1974). Using the absolute and inverse values of the slope and its 95% confidence limits, the *z* value and its 95% confidence limits were calculated (*Stumbo* 1973, *Colton* 1974).

95% confidence limits on predicted means (*Colton* 1974) of *D* values were calculated (the predicted mean is the same as *D* in the equation). 95% confidence limits on predicted individual *D* values (*Colton* 1974) were also figured out (From a practical point of view it may be more interesting to know these limits than those on predicted means).

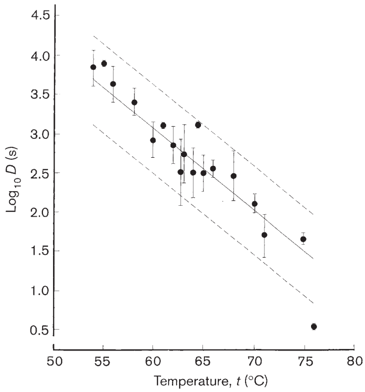

Figure 1

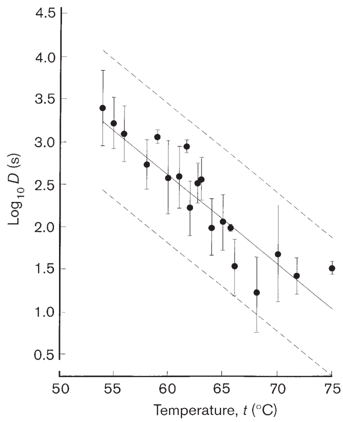

Figure 2

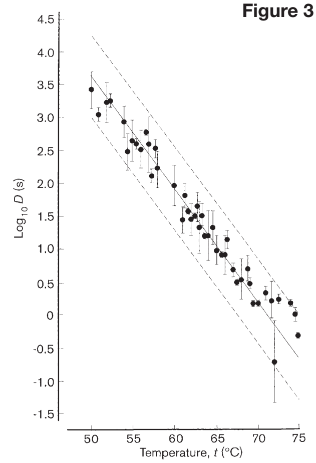

Figure 3

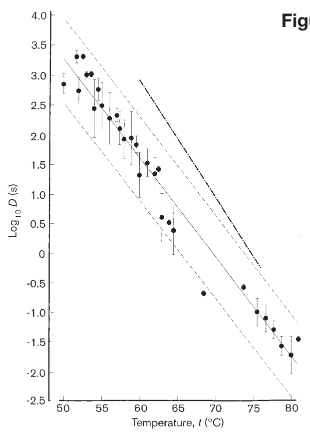

Figure 4

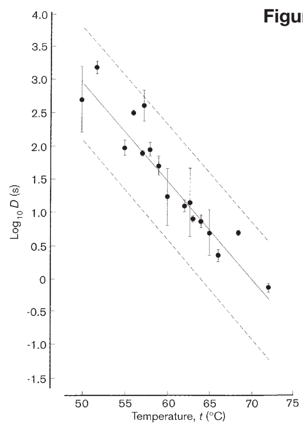

Figure 5

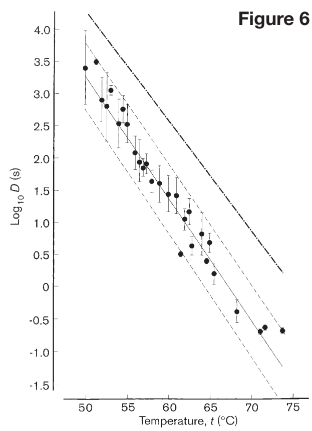

Figure 6

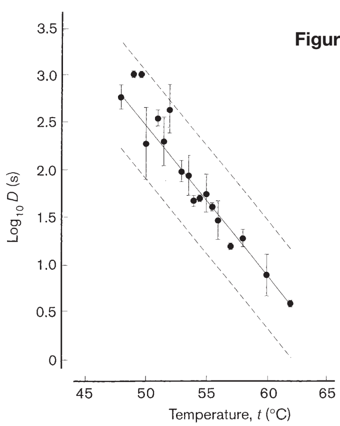

Figure 7

Figure 1. Heat resistance data (Mean ± SD) recorded at the different treatment temperatures used and fitted thermal destruction line (-) for *Enterococcus faecium.* The equation for the line is $\log_{10} D = 9.3080 - 0.10412t$ ($r = -0.84748$; total number of $\log_{10} D$ values = 195). The 95% confidence limits on predicted individual $\log_{10} D$ values are shown by (- -). The figure is based on data from: *Greenberg & Silliker* (1961), *Zivanovic et al.* (1965), *Ienistea et al.* (1970), *Vrchlabsky & Leistner* (1970), *Sanz Pérez et al.* (1982), *Magnus et al.* (1986, 1988), *Quintavalla et al.* (1988), *Gordon & Ahmad* (1991), *Kornacki & Marth* (1992), *Patel & Wilbey* (1994), *Simpson et al.* (1994), *Kearns et al.* (1995), *Mulak et al.* (1995), *Renner & Peters* (1999).

Figure 2. Heat resistance data (Mean ± SD) recorded at the different treatment temperatures used and fitted thermal destruction line (-) for *Enterococcus faecalis.* The equation for the line is $\log_{10} D = 8.9359 - 0.10531t$ ($r = -0.72968$; total number of $\log_{10} D$ values = 244). The 95% confidence limits on predicted individual $\log_{10} D$ values are shown by (- -). The figure is based on data from: *Richards & White* (1949), *White* (1953), *Krishna Iyengar et al.* (1957), *White* (1963), *Zivanovic et al.* (1965), *Beuchat & Lechowich* (1968), *Clark et al.* (1968), *Ienistea et al.* (1970), *Shannon et al.* (1970), *Vrchlabsky & Leistner* 1970), *Dabbah et al.* (1971a, c), *Gardner & Patton* (1975), *Sanz Pérez et al.* (1982), *Magnus et al.* (1986, 1988), *Quintavalla et al.* (1988), *Boutibonnes et al.* (1993), *Kearns et al.* (1995), *Flahaut et al.* (1996, 1997).

Figure 3. Heat resistance data (Mean ± SD) recorded at the different treatment temperatures used and fitted thermal destruction line (-) for *Listeria monocytogenes.* The equation for the line is $\log_{10} D = 12.3787 - 0.17401t$ ($r = -0.95631$; total number of $\log_{10} D$ values = 474). The 95% confidence limits on predicted individual $\log_{10} D$ values are shown by (- -). The figure is based on data from: *Bradshaw et al.* (1985), *Beuchat et al.* (1986), *Bunning et al.* (1986), *Donnelly & Briggs* (1986), *Bradshaw et al.* (1987b), *Donnelly et al.* (1987), *Fernández Garayzabal et al.* (1987), *Bunning et al.* (1988), *Farber et al.* (1988), *Golden et al.* (1988), *Northolt et al.* (1988), *Steinmeyer* (1988), *El-Shenawy et al.* (1989), *Fedio & Jackson* (1989), *Lemaire et al.* (1989), *Quintavalla & Barbuti* (1989), *Suárez Fernández et al.* (1989), *Boyle et al.* (1990), *Bunning et al.* (1990), *Foegeding & Leasor* (1990), *Knabel et al.* (1990), *Linton et al.* (1990), *Mackey et al.* (1990), *Anderson et al.* (1991), *Bradshaw et al.* (1991), *Foegeding & Stanley* (1991), *Konvincic et al.* (1991), *McKenna et al.* (1991), *Quintavalla & Campanini* (1991), *Bunning et al.* (1992), *Farber & Pagotto* (1992), *Holsinger et al.* (1992), *Meyer & Donnelly* (1992), *Fairchild & Foegeding* (1993), *Sörqvist* (1993, 1994), *Stephens et al.* (1994), *Bartlett & Hawke* (1995), *Jørgensen et al.* (1995, 1996), *Palumbo et al.* (1995, 1996), *Lou & Yousef* (1996), *Muriana et al.* (1996), *Patchett et al.* (1996), *Schuman & Sheldon* (1997), *Casadei et al.* (1998), *George et al.* (1998), *Juneja et al.* (1998), *Pagán et al.* (1998), *Rowan & Anderson* (1998), *Knight et al.* (1999).

Figure 4. Heat resistance data (Mean ± SD) recorded at the different treatment temperatures used and fitted thermal destruction line (-) for *Escherichia coli.* The equation for the line is $\log_{10} D = 11.6471 - 0.16768t$ ($r = -0.97349$; total number of $\log_{10} D$ values = 332). The 95% confidence limits on predicted individual $\log_{10} D$ values are shown by (- -). Data used are from: *Elliker & Frazier* (1938), *Katzin et al.* (1943), *Solowey et al.* (1948), *Chambers et al.* (1957). *Read et al.* (1957), *Lemcke & White* (1959), *Read et al.* (1961), *Calhoun & Frazier* (1966), *Evans et al.* (1970), *Goepfert et al.* (1970), *Dabbah et al.* (1971c), *Dega et al.* (1972), *Tsuchido et al.* (1974), *Ahmad et al.* (1978), *Katsui et al.* (1981), *Yamamori & Yura* (1982), *D´Aoust et al.* (1988), *Jenkins et al.* (1988), *Morgan et al.* (1988), *Murano & Pierson* (1992, 1993), *Gadzella & Ingham* (1994), *Ahmed & Conner* (1995), *Clavero & Beuchat* (1995, 1996), *Clementi et al.* (1995), *Jackson et al.* (1996), *Teo et al.* (1996), *Blackburn et al.* (1997), *Williams & Ingham* (1997, 1998), *George et al.* (1998), *George & Peck* (1998), *Kaur et al.* (1998), *Semanchek & Golde*n (1998).
Thermal destruction line for an unusually heat-resistant strain of *E. coli* reported by *Holland & Dahlberg* (1940) is also shown (- · -).

Figure 5. Heat resistance data (Mean ± SD) recorded at the different treatment temperatures used and fitted thermal destruction line (-) for *Yersinia enterocolitica.* The equation for the line is $\log_{10} D = 10.4176 - 0.14896t$ ($r = -0.86082$; total number of $\log_{10} D$ values = 88). The 95% confidence limits on predicted individual $\log_{10} D$ values are shown by (- -). The figure is based on data from: *Hanna et al.* (1977), *Francis et al.* (1980), *Norberg* (1981), *Lovett et al.* (1982), *D´Aoust et al.* (1988), *Sörqvist* (1989), *Sörqvist & Danielsson-Tham* (1990), *Toora et al.* (1992), *Shenoy & Murano* (1996), *Pagán et al.* (1999).

Figure 6. Heat resistance data (Mean ± SD) recorded at the different treatment temperatures used and fitted thermal destruction line (-) for *Salmonella* spp. The equation for the line is $\log_{10} D = 12.9511 - 0.19282t$ ($r = -0.92147$; total number of $\log_{10} D$ values = 647). The 95% confidence limits on predicted individual $\log_{10} D$ values are shown by (- -). Data used are from: *Solowey et al.* (1948), *Anellis et al.* (1954), *Osborne et al.* (1954), *Lategan & Vaughn* (1964), *Davidson et al.* (1966), *Ng* (1966), *Thomas et al.* (1966), *Corry & Barnes* (1968), *Read et al.* (1968), *Garibaldi et al.* (1969a, b), *Ng et al.* (1969), *Baird-Parker et al.* (1970), *Evans et al.* (1970), *Goepfert et al.* (1970), *Rossebø* (1970), *Dabbah et al.* (1971a, b), *Moats et al.* (1971), *Dega et al.* (1972), *Gibson* (1973), *Corry* (1974), *Thompson et al.* (1979), *Humphrey* (1981), *Humphrey et al.* (1981), *Mackey & Derrick* (1986), *Okrend et al.* (1986), *Bradshaw et al.* (1987a), *D´Aoust et al.* (1987), *Mackey & Derrick* (1987a, b), *Baker* (1990), *Bunning et al.* (1990), *Humphrey et al.* (1990), *Humphrey* (1990), *Mackey & Derrick* (1990), *Sörqvist & Danielsson-Tham* (1990), *Humphrey et al.* (1991), *Shah et al.* (1991), *Humphrey et al.* (1993a, b), *Leyer & Johnson* (1993), *Xavier & Ingham* (1993), *Wolfson & Sumner* (1994), *Humphrey et al.* (1995), *Palumbo et al.* (1995, 1996), *Muriana et al.* (1996), *Teo et al.* (1996), *Blackburn et al.* (1997), *Schuman & Sheldon* (1997), *George et al.* (1998), *Humpheson et al.* (1998), *Michalski et al.* (1999).
Thermal destruction line for the extremely heat-resistant *Salm. senftenberg* 775W is also shown (- · -) ; for references, see text.

Figure 7. Heat resistance data (Mean ± SD) recorded at the different treatment temperatures used and fitted thermal destruction line (-) for *Campylobacter jejuni/coli.* The equation for the line is $\log_{10} D = 10.3432 - 0.15717t$ ($r = -0.89853$; total number of $\log_{10} D$ values = 112). The 95% confidence limits on predicted individual $\log_{10} D$ values are shown by (- -). The figure is based on data from: *Doyle & Roman* (1981), *Gill et al.* (1981), *Blankenship & Craven* (1982), *Christopher et al.* (1982), *Waterman* (1982), *Oosterom et al.* (1983), *Humphrey & Cruickshank* (1985), *Okrend et al.* (1986), *Humphrey & Lanning* (1987), *D´Aoust et al.* (1988), *Sörqvist* (1989), *Sörqvist & Danielsson-Tham* (1990).

Table 3. Heat resistance values at 4 temperatures for bacteria studied in the work. The values are based on results reported from investigations where the experimental conditions laid down in the work were fulfilled.

Bacterium/ Bacterial group**	Temperature (°C)	*D** values (s)		
			95% confidence interval	
		Mean	For the mean	For a predicted individual value
Enterococcus faecium	55	3813	3095-4697	1041-13969
	60	1150	1017-1300	317-4166
	65	347	315-381	96-1254
	72	65	53-79	18-237
Enteroccus faecalis	55	1393	1089-1783	220-8816
	60	415	361-476	66-2593
	65	123	108-141	20-771
	72	23	17-30	3.5-144
Listeria innocua	55	1635	1050-2549	474-5644
	60	162	127-207	50-529
	65	16	13-20	5.0-52
	72	0.6 †	0.4-1.0	0.2-2.2
Listeria monocytogenes	55	643	577-715	150-2754
	60	87	81-93	20-371
	65	12	11-13	2.7-50
	72	0.7	0.6-0.8	0.2-3.0
Escherichia coli	55	266	239-297	53-1338
	60	39	35-42	8-194
	65	5.6	5.1-6.2	1.1-28
	72	0.4	0.3-0.5	0.1-1.9
Yersinia enterocolitica	55	168	124-227	23-1244
	60	30	24-37	4.1-221
	65	5.4	4.0-7.4	0.7-40
	72	0.5	0.3-0.9	0.1-3.9
Salmonella spp.	55	222	208-237	64-771
(except *Salm. senftenberg* 775W)	60	24	23-26	7.0-84
	65	2.6	2.3-2.9	0.8-9.1
	72	0.1	0.1-0.2	0.1-0.4
Campylobacter jejuni/coli	55	50	44-57	13-190
	60	8.2	6.5-10	2.1-32
	65	1.3 †	0.9-2.0	0.3-5.4
	72	0.1 †	0.1-0.2	0.1-0.5

* The *D* value is the time of heat treatment required at a certain temperature to destroy 90% of the bacterial cells.
** The bacteria are arranged according to their mean heat resistances at 60 and 65°C.
† Extrapolated value.

Summaries of data

Reported z values are summarized in Table 1. Reported and calculated z values taken together are given in Table 2, where z values figured out in the work by means of the equation mentioned, etc. are also shown. Thermal destruction lines for the bacteria studied, except those for *L. innocua, L. ivanovii, L. seeligeri* and *L. welshimeri,* are depicted in Figures 1-7, where 95% confidence limits on predicted individual $\log_{10}$ D values are also illustrated graphically. In Table 3, some D values at these limits are shown for the seven bacterial groups and also for *L. innocua.* Equations for the thermal destruction line of *L. innocua* and that of *L. ivanovii, L. seeligeri* and *L. welshimeri* taken together, are given below under the headings *Listeria innocua* and *Listeria ivanovii, L. seeligeri* and *L. welshimeri,* respectively.

Comments and further information

D and r values

The order of death of bacteria subjected to heat at a constant lethal temperature is often logarithmic (*Hansen & Riemann* 1963, *Stumbo* 1973, *Pflug & Holcomb* 1983), i.e. when the logarithm of survivors is plotted against the time of heating, the curve obtained, the survivor curve, is a straight line. The D value can then easily be calculated using the slope of the line. Deviations from the logarithmic order of death, however, are rather frequent and non-logarithmic survivor curves of some different types are obtained (*Hansen & Riemann* 1963, *Stumbo* 1973, *Pflug & Holcomb* 1983). Deviations of this kind often make determinations of D values difficult.

The r values, varying from -0.92147 to -0.99405, obtained for *Salmonella* spp., *E. coli* and the 3 *Listeria* groups indicate very good linear relationships (*Colton* 1974) between the $\log_{10}$ D values recorded and the treatment temperatures used. The r values, varying from -0.72968 to -0.89853, recorded for *Ent. faecalis, Ent. faecium, Y. enterocolitica* and *Camp. jejuni/coli* indicate weaker but, nevertheless, good linear relationships (*Colton* 1974). The following should be noted here: The number of *Y. enterocolitica* strains investigated is low. The results reported, however, indicate that great variation in heat resistance exists between strains of this species. As to enterococci, non-logarithmic survivor curves were reported in several works (*Zivanovic et al.* 1965, *Dabbah et al.* 1971a,c, *Sanz Pérez et al.* 1982, *Magnus et al.* 1986, *Gordon & Ahmad* 1991, *Boutibonnes et al.* 1993).

Listeria monocytogenes

Mackey & Bratchell (1989) published a similar review of the heat resistance of *L. monocytogenes.* Equations were given for heat treatments in: (a) various menstrua and (b) milk. The treatments in (b) had been performed by a sealed tube method (b1) or a slug flow heat exchanger (b2). The equations for (a), (b1) and (b2) were $\log_{10} D = 10.888 - 0.14519t$, $\log_{10} D = 11.931 - 0.1635t$ and $\log_{10} D = 10.126 - 0.1348t$ (D is in s in the equations). The means of D values obtained by the 3 equations for 55, 60, 65 and 72 °C are shown in Table 4. The means in (a), (b1) and (b2) except that in (b2) for 55 °C are higher than the corresponding ones (c) recorded for *L. monocytogenes* in the present work (Table 3). The differences between (a) and (c) may, at least to some extent, be explained by the fact that some of the heating menstrua in (a) were solids. The differences between (b1) or (b2) and (c) are therefore of greater interest, as all data for these 3 groups were obtained in liquids. A probable explanation of these differences is that heat resistance data for several "new" strains have been published later than the review by *Mackey & Bratchell* (1989) and have thus been included in the present work. Furthermore, the methods of determining the heat

Table 4. *D* values for *Listeria monocytogenes* according to the review by *Mackey & Bratchell* (1989).

Heating menstruum(-a)/ Treatment method(s)	*D*** value (s)			
	55°C	60°C	65°C	72°C
(a) Various/Various	799*	150*	28*	2.7*
(b1) Milk/ST	868	132	20	1.4†
(b2) Milk/SF	515‡	109	23	2.6

** The *D* value is the time of heat treatment required at a certain temperature to destroy 90% of the bacterial cells.
ST, sealed tubes; SF, slug flow heat exchanger.
*, †, ‡ Value calculated using the equation given by the authors for (a), (b1) and (b2) respectively.

resistance of bacteria have been widely discussed in recent years and some improvements or new procedures have been introduced. Factors of this kind may also have contributed to the differences.

Listeria innocua

The non-pathogenic *L. innocua* is of special interest as it has, as mentioned, been proposed to be used as an indicator organism to evaluate thermal processes for lethality to *L. monocytogenes.* To function satisfactorily in this respect it is desirable that the indicator has heat resistance equal to or greater than the average heat resistance of *L. monocytogenes* or, more desirably, has heat resistance equal to that of the most resistant strains of this species. In the present work, heat resistance results for *L. innocua* were found in 5 reports (*Quintavalla & Barbuti* 1989, *Mackey et al.* 1990, *Foegeding & Stanley* 1991, *Fairchild & Foegeding* 1993, *Palumbo et al.* 1995). The equation for the thermal destruction line constructed was $\log_{10} D$ (D in s) = 14.2559 - 0.20077t (r = -0.95519). The average heat resistance values at 55, 60 and 65 °C calculated for *L. innocua* were greater than those for *L. monocytogenes* (Table 3), but none of analysed differences between means of *D* values were statistically significant. As to *L. innocua,* however, only 36 *D* values were reported totally and the *D* values obtained at the individual treatment temperatures used were few, 1-4. The most heat-resistant strain of the *L. innocua* strains investigated was reported by *Quintavalla & Barbuti* (1989). *D* values determined at 58, 60, 63 and 65 °C using a culture medium as heating menstruum were 2.7 to 5.4 times greater than the average *D* values found in the present work for *L. monocytogenes* at these temperatures. *Foegeding & Stanley* (1991) tested *L. innocua* strain ATCC 33091 in buffer and in skim milk at 56, 60 and 66 °C. In buffer, the *D* values were lower at 56 and 60 but higher at 66 °C than the corresponding average values for *L. monocytogenes.* When *L. innocua* PFEI (strain ATCC 33091 containing a plasmid which did not alter its heat resistance) was tested in skim milk, all *D* values obtained at these temperatures were higher, 1.5 to 2.1 times, than the values mentioned for *L. monocytogenes. Palumbo et al.* (1995) determined *D* values for a *L. innocua* strain isolated from raw egg. The tests were performed in egg yolk. *D* values obtained at 61.1, 63.3 and 64.4 °C were 2.5 to 2.9 times longer than the corresponding average values for *L. monocytogenes.* The results reported indicate that *L. innocua* may have greater average heat resistance than *L. monocytogenes.* However, as mentioned, only few heat resistance results are reported for *L. innocua* and more research on this matter is required.

Listeria ivanovii, L. seeligeri and L. welshimeri

Bradshaw et al. (1991) studied the heat resistance of *L. ivanovii, L. seeligeri* and *L. welshimeri.* One strain of each species was tested in milk at 52.2, 57.8, 63.3 and 68.9 °C. The equation for the 3 species taken together is $\log_{10} D$ (D in s) = 11.3419 - 0.15713t ; r = -0.99405. All means of *D* values obtained for the 4 treatment temperatures were lower than the corresponding means noted in the present work for *L. monocytogenes.* The differences between the means were statistically significant for the values obtained at 52.2 and 57.8 °C ($p < 0.05$ and < 0.001) but not for those obtained at 63.3 and 68.9 °C. In view of the low number of *D* values, 24, reported for *L. ivanovii, L. seeligeri* and *L. welshimeri* and the fact that only one strain of each of these species was tested, no conclusion, however, should be drawn about differences in average heat resistance between these species and *L. monocytogenes.*

Salmonella

Ng (1966) studied the heat resistance of 300 *Salmonella* isolates and gave $D_{57°C}$ values for 123 strains. The well-known extremely heat-resistant *Salm. senftenberg* 775W and 19 other strains of *Salm. senftenberg* were among the tested isolates. The resistance of the 19 strains was similar to that of the majority of isolates. Ng concluded that strains of salmonellae as resistant to heat as *Salm. senftenberg* 775W are rare. A similar conclusion was drawn by *Rossebø* (1970) who compared the heat resistance of *Salm. senftenberg* 775W with that of 20 strains of *Salm. senftenberg* isolated from herring meal.

The heat resistance of *Salm. senftenberg* 775W was also tested by *Anellis et al.* (1954), *Osborne et al.* (1954), *Davidson et al.* (1966), *Thomas et al.* (1966), *Corry & Barnes* (1968), *Read et al.* (1968), *Garibaldi et al.* (1969a), *Ng et al.* (1969), *Baird-Parker et al.* (1970), *Goepfert et al.* (1970), *Dabbah et al.* (1971a, b), *Gibson* (1973), *Corry* (1974), *Humphrey et al.* (1990) and *Blackburn et al.* (1997). The thermal destruction line fitted to the data (number of *D* values = 54) reported by the investigators mentioned is shown in Fig. 6. The equation for the line is $\log_{10} D$ (*D* in s) = 12.8001 - 0.17111t (r = -0.94992).

In a screening of 221 *Salmonella* isolates, *Baird-Parker et al.* (1970) found that 2 strains, one of *Salm. senftenberg* tested earlier by *Davidson et al.* (1966) and one of *Salm. bedford,* had $D_{60°C}$ values similar to that of *Salm. senftenberg* 775W. *Baird-Parker et al.* considered it possible, although unlikely, that the *Salm. senftenberg* strain was identical to *Salm. senftenberg* 775W (the strain was isolated from home-killed meat in the United Kingdom and *Salm. senftenberg* 775W from dried eggs in the United States). The authors determined *D* values in heart infusion broth for the *Salm. bedford* strain and for *Salm. senftenberg* 775W. *D* values obtained at 50, 55 and 60 °C were 350, 18.8 and 4.3 min for the *Salm. bedford* strain and 268, 36.2 and 6.3 min for *Salm. senftenberg* 775W. For comparison, it may be mentioned that the *D* values obtained for *Salm. senftenberg* 775W using the equation constructed in the present study are 293, 40.8 and 5.7 min at these temperatures.

Escherichia coli

Holland & Dahlberg (1940) investigated an *E. coli* strain noted for its heat resistance. Tests were performed in milk. The thermal destruction line based on the data (number of *D* values = 22) reported by Holland and Dahlberg is shown in Fig. 4. The equation for the line is $\log_{10}$ *D* (*D* in s) = 14.7478 - 0.19777t (r = -0.99403). The z value is 5.1 °C. The author of the present work is unaware of whether this *E. coli* strain has been subjected to further heat resistance studies.

Concluding remarks

The design of the present study required that some differences in composition, etc. of heating menstrua used and in methods used for heat treatment and for recovery of heat-treated bacteria had to be accepted when heat resistance data were collected from the literature. This meant that experimental factors of varying character might have influenced the magnitude of heat resistance values used in the work. Statistical analyses of the results of these fairly numerous influences could not be achieved on the basis of available information. Scrutiny of heat resistance values chosen according to the stipulations laid down in the study, however, indicated that value differences probably caused by differences in experimental conditions were, in most cases, small or moderate.

The summary heat resistance values recorded - especially those for *L. monocytogenes, E. coli* and salmonellas which are based on large numbers of data - may give useful information on what is at present known about the heat resistance that the bacteria reviewed show in liquid heating menstrua with pH values of approx. 6-8. It should, however, be emphasized that they may, and often do, show heat resistance of different magnitude in other types of heating menstrua.

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References

Ahmad M, Srivastava BS, Agarwala SC: Effect of incubation media on the recovery of *Escherichia coli* K12 heated at 52°C. J. Gen. Microbiol. 1978, *107,* 37-44.

Ahmed NM, Conner DE: Evaluation of various media for recovery of thermally-injured *Escherichia coli* O157:H7. J. Food Prot. 1995, *58,* 357-360.

Anderson WA, Hedges ND, Jones MV, Cole MB: Thermal inactivation of *Listeria monocytogenes* studied by differential scanning calorimetry. J. Gen. Microbiol. 1991, *137,* 1419-1424.

Anellis A. Lubas J, Rayman MM: Heat resistance in liquid eggs of some strains of the genus *Salmonella.* Food Res. 1954, *19,* 377-395.

Baird-Parker AC, Boothroyd M, Jones E: The effect of water activity on the heat resistance of heat sensitive and heat resistant strains of salmonellae. J. Appl. Bacteriol. 1970, *33,* 515-522.

Baker RC: Survival of *Salmonella enteritidis* on and in shelled eggs, liquid eggs and cooked egg products. Dairy Food Environ. Sanit. 1990, *10,* 273-275.

Bartlett FM, Hawke AE: Heat resistance of *Listeria monocytogenes* Scott A and HAL 957E1 in various liquid egg products. J. Food Prot. 1995, *58,* 1211-1214.

Beuchat LR, Brackett RE, Hao DY-Y, Conner DE: Growth and thermal inactivation of *Listeria monocytogenes* in cabbage and cabbage juice. Can. J. Microbiol. 1986, *32,* 791-795.

Beuchat LR, Lechowich RV: Survival of heated *Streptococcus faecalis* as affected by phase of growth and incubation temperature after thermal exposure. J. Appl. Bacteriol. 1968, *31,* 414-419.

Blackburn C de W, Curtis LM, Humpheson L, Billon C, McClure PJ: Development of thermal inactivation models for *Salmonella enteritidis* and *Escherichia coli* O157:H7 with temperature, pH and NaCl as controlling factors. Int. J. Food Microbiol. 1997, *38,* 31-44.

Blankenship LC, Craven SE: Campylobacter jejuni survival in chicken meat as a function of temperature. Appl. Environ. Microbiol. 1982, *44,* 88-92.

Boutibonnes P, Giard JC, Hartke A, Thammavongs B, Auffray Y: Characterization of the heat shock response in *Enterococcus faecalis.* Antonie van Leeuwenhoek 1993, *64,* 47-55.

Boyle DL, Sofos JN, Schmidt GR: Thermal destruction of *Listeria monocytogenes* in a meat slurry and in ground beef. J. Food Sci. 1990, *55,* 327-329.

Bradshaw JG, Peeler JT, Corwin JJ, Barnett JE, Twedt RM: Thermal resistance of disease-associated *Salmonella typhimurium* in milk. J. Food Prot. 1987a, *50,* 95-96.

Bradshaw JG, Peeler JT, Corwin JJ, Hunt JM, Tierney JT, Larkin EP, Twedt RM: Thermal resistance of *Listeria monocytogenes* in milk. J. Food Prot. 1985, 4*8,* 743-745.

Bradshaw JG, Peeler JT, Corwin JJ, Hunt JM, Twedt RM: Thermal resistance of *Listeria monocytogenes* in dairy products. J. Food Prot. 1987b, *50,* 543-544, 556.

Bradshaw JG, Peeler JT, Twedt RM: Thermal resistance of *Listeria* spp. in milk. J. Food Prot. 1991, *54,* 12-14, 19.

Bunning VK, Crawford RG, Bradshaw JG, Peeler JT, Tierney JT, Twedt RM: Thermal resistance of intracellular *Listeria monocytogenes* cells suspended in raw bovine milk. Appl. Environ. Microbiol. 1986, *52,* 1398-1402.
Bunning VK, Crawford RG, Tierney JT, Peeler JT: Thermotolerance of *Listeria monocytogenes* and *Salmonella typhimurium* after sublethal heat shock. Appl. Environ. Microbiol. 1990, *56,* 3216-3219.
Bunning VK, Crawford RG, Tierney JT, Peeler JT: Thermotolerance of heat-shocked *Listeria monocytogenes* in milk exposed to high-temperature, short-time pasteurization. Appl. Environ. Microbiol. 1992, *58,* 2096-2098.
Bunning VK, Donnelly CW, Peeler JT, Briggs EH, Bradshaw JG, Crawford RG, Beliveau CM, Tierney JT: Thermal inactivation of *Listeria monocytogenes* within bovine milk phagocytes. Appl. Environ. Microbiol. 1988, *54,* 364-370.
Calhoun CL, Frazier WC: Effect of available water on thermal resistance of three nonsporeforming species of bacteria. Appl. Microbiol. 1966, *14,* 416-420.
Casadei MA, Esteves de Matos R, Harrison ST, Gaze JE: Heat resistance of *Listeria monocytogenes* in dairy products as affected by the growth medium. J. Appl. Microbiol. 1998, *84,* 234-239.
Chambers CW, Tabak HH, Kabler PW: Effect of Krebs cycle metabolites on the viability of *Escherichia coli* treated with heat and chlorine. J. Bacteriol. 1957, *73,* 77-84.
Christopher FM, Smith GC, Vanderzant C: Effect of temperature and pH on the survival of *Campylobacter fetus.* J. Food Prot. 1982, *45,* 253-259.
Clark CW, Witter LD, Ordal ZJ: Thermal injury and recovery of *Streptococcus faecalis.* Appl. Microbiol. 1968, *16,* 1764-1769.
Clavero MRS, Beuchat LR: Suitability of selective plating media for recovering heat- or freeze-stressed *Escherichia coli* O157:H7 from tryptic soy broth and ground beef. Appl. Environ. Microbiol. 1995, *61,* 3268-3273.
Clavero MRS, Beuchat LR: Survival of *Escherichia coli* O157:H7 in broth and processed salami as influenced by pH, water activity, and temperature and suitability of media for its recovery. Appl. Environ. Microbiol. 1996, *62,* 2735-2740.
Clementi F, Parente E, Ricciardi A, Addario G, Moresi M: Heat resistance of *Escherichia coli* in goat milk: a comparison between the sealed capillary tube technique and a laboratory slug flow heat exchanger. Ital. J. Food Sci. 1995, *7,* 235-243.
Colton T: Statistics in Medicine, 1st edn. Little Brown, Boston 1974, pp. 191-202, 207-211.
Corry JEL: The effect of sugars and polyols on the heat resistance of salmonellae. J. Appl. Bacteriol. 1974, *37,* 31-43.
Corry JEL, Barnes EM: The heat resistance of salmonellae in egg albumen. Brit. Poult. Sci. 1968, *9,* 253-260.
Dabbah R, Moats WA, Edwards VM: Survivor curves of selected *Salmonella enteritidis* serotypes in liquid whole egg homogenates at 60°C. Poultry Sci. 1971a, *50,* 1772-1776.
Dabbah R, Moats WA, Edwards VM: Heat survivor curves of food-borne bacteria suspended in commercially sterilized whole milk. I. Salmonellae. J. Dairy Sci. 1971b, *54,* 1583-1588.
Dabbah R, Moats WA, Edwards VM: Heat survivor curves of food-borne bacteria suspended in commercially sterilized whole milk. II. Bacteria other than salmonellae. J. Dairy Sci. 1971c, *54,* 1772-1779.
D´Aoust J-Y, Emmons DB, McKellar R, Timbers GE, Todd ECD, Sewell AM, Warburton DW: Thermal inactivation of *Salmonella* species in fluid milk. J. Food Prot. 1987, *50,* 494-501.
D´Aoust J-Y, Park CE, Szabo RA, Todd ECD, Emmons DB, McKellar RC: Thermal inactivation of *Campylobacter* species, *Yersinia enterocolitica* and hemorrhagic *Escherichia coli* O157:H7 in fluid milk. J. Dairy Sci. 1988, *71,* 3230-3236.
Davidson CM, Boothroyd M, Georgala DL: Thermal resistance of *Salmonella senftenberg.* Nature 1966, *212,* 1060-1061.
Dega CA, Goepfert JM, Amundson CH: Heat resistance of salmonellae in concentrated milk. Appl. Microbiol. 1972, *23,* 415-420.
Donnelly CW, Briggs EH: Psychrotrophic growth and thermal inactivation of *Listeria monocytogenes* as a function of milk composition. J. Food Prot. 1986, *49,* 994-998, 1002.
Donnelly CW, Briggs EH, Donnelly LS: Comparison of heat resistance of *Listeria monocytogenes* in milk as determined by two methods. J. Food Prot. 1987, *50,* 14-17, 20.
Doyle ME, Mazzotta AS: Review of studies on the thermal resistance of salmonellae. J. Food Prot. 2000, *63,* 779-795.
Doyle ME, Mazzotta AS, Wang T, Wiseman DW, Scott VN: Review. Heat resistance of *Listeria monocytogenes.* J. Food Prot. 2001, *64,* 410-429.

Doyle MP, Roman DJ: Growth and survival of *Campylobacter fetus* subsp. *jejuni* as a function of temperature and pH. J. Food Prot. 1981, *44,* 596-601.

El-Shenawy MA, Yousef AE, Marth EH: Thermal inactivation and injury of *Listeria monocytogenes* in reconstituted nonfat dry milk. Milchwissenschaft 1989, *44,* 741-745.

Elliker PR, Frazier WC: Influence of time and temperature of incubation on heat resistance of *Escherichia coli.* J. Bacteriol. 1938, *36,* 83-98.

Evans DA, Hankinson DJ, Litsky W: Heat resistance of certain pathogenic bacteria in milk using a commercial plate heat exchanger. J. Dairy Sci. 1970, *53,* 1659-1665.

Fairchild TM, Foegeding PM: A proposed nonpathogenic biological indicator for thermal inactivation of *Listeria monocytogenes.* Appl. Environ. Microbiol. 1993, *59,* 1247-1250.

Farber JM, Pagotto F: The effect of acid shock on the heat resistance of *Listeria monocytogenes.* Lett. Appl. Microbiol. 1992, *15,* 197-201.

Farber JM, Sanders GW, Speirs JI, D´Aoust J-Y, Emmons DB, McKellar R: Thermal resistance of *Listeria monocytogenes* in inoculated and naturally contaminated raw milk. Int. J. Food Microbiol. 1988, *7,* 277-286.

Fedio WM, Jackson H: Effect of tempering on the heat resistance of *Listeria monocytogenes.* Lett. Appl. Microbiol. 1989, *9,* 157-160.

Fernández Garayzabal JF, Domínguez Rodríguez L, Vázques Boland JA, Rodríguez Ferri EF, Briones Dieste V, Blanco Cancelo JL, Suárez Fernández G: Survival of *Listeria monocytogenes* in raw milk treated in a pilot plant size pasteurizer. J. Appl. Bacteriol. 1987, *63,* 533-537.

Flahaut S, Frere J, Boutibonnes P, Auffray Y: Relationship between the thermotolerance and the increase of DnaK and GroEL synthesis in *Enterococcus faecalis* ATCC 19433. J. Basic Microbiol. 1997, *37,* 251-258.

Flahaut S, Hartke A, Giard J-C, Benachour A, Boutibonnes P, Auffray Y: Relationship between stress response towards bile salts, acid and heat treatment in *Enterococcus faecalis.* FEMS Microbiol. Lett. 1996, *138,* 49-54.

Foegeding PM, Leasor SB: Heat resistance and growth of *Listeria monocytogenes* in liquid whole egg. J. Food Prot. 1990, *53,* 9-14.

Foegeding PM, Stanley NW: Listeria innocua transformed with an antibiotic resistance plasmid as a thermal-resistance indicator for *Listeria monocytogenes.* J. Food Prot. 1991, *54,* 519-523.

Francis DW, Spaulding PL, Lovett J: Enterotoxin production and thermal resistance of *Yersinia enterocolitica* in milk. Appl. Environ. Microbiol. 1980, *40,* 174-176.

Gadzella TA, Ingham SC: Heat shock, anaerobic jar incubation and fluid thioglycollate medium have contrasting effects on D-values of *Escherichia coli.* J. Food Prot. 1994, *57,* 671-673.

Gardner GA, Patton J: A note on the heat resistance of a *Streptococcus faecalis* isolated from a "soft core" in canned ham. Proc. 21st Europ. Meet. Meat Res. Workers, Bern, 1975, pp. 52-54.

Garibaldi JA, Ijichi K, Bayne HG: Effect of pH and chelating agents on the heat resistance and viability of *Salmonella typhimurium* Tm-1 and *Salmonella senftenberg* 775W in egg white. Appl. Microbiol. 1969a, *18,* 318-322.

Garibaldi JA, Straka RP, Ijichi K: Heat resistance of *Salmonella* in various egg products. Appl. Microbiol. 1969b, *17,* 491-496.

George SM, Peck MW: Redox potential affects the measured heat resistance of *Escherichia coli* O157:H7 independently of oxygen concentration. Lett. Appl. Microbiol. 1998, *27,* 313-317.

George SM, Richardson LCC, Pol IE, Peck MW: Effect of oxygen concentration and redox potential on recovery of sublethally heat-damaged cells of *Escherichia coli* O157:H7, *Salmonella enteritidis* and *Listeria monocytogenes.* J. Appl. Microbiol. 1998, *84,* 903-909.

Gibson B: The effect of high sugar concentrations on the heat resistance of vegetative micro-organisms. J. Appl. Bacteriol. 1973, *36,* 365-376.

Gill KPW, Bates PG, Lander KP: The effect of pasteurization on the survival of *Campylobacter* spedies in milk. Brit. Vet. J. 1981, *137,* 578-584.

Goepfert JM, Iskander IK, Amundson CH: Relation of the heat resistance of salmonellae to the water activity of the environment. Appl. Microbiol. 1970, *19,* 429-433.

Golden DA, Beuchat LR, Brackett RE: Inactivation and injury of *Listeria monocytogenes* as affected by heating and freezing. Food Microbiol. 1988, *5,* 17-23.

Gordon CLA, Ahmad MH: Thermal susceptibility of *Streptococcus faecium* strains isolated from frankfurters. Can. J. Microbiol. 1991, *37,* 609-612.

Greenberg RA, Silliker JH: Evidence for heat injury in enterococci. Food Res. 1961, *26,* 622-625.

Hanna MO, Stewart JC, Carpenter ZL, Vanderzant

C: A research note. Heat resistance of *Yersinia enterocolitica* in skim milk. J. Food Sci. 1977, *42,* 1134, 1136.
Hansen N-H, Riemann H: Factors affecting the heat resistance of nonsporing organisms. J. Appl. Bacteriol. 1963, *26,* 314-333.
Holland RF, Dahlberg AC: The effect of the time and temperature of pasteurization upon some of the properties and constituents of milk. New York State Agricultural Experiment Station, Technical Bulletin No. 254, 1940, pp. 18-22, 39-55.
Holsinger VH, Smith PW, Smith JL, Palumbo SA: Thermal destruction of *Listeria monocytogenes* in ice cream mix. J. Food Prot. 1992, *55,* 234-237.
Humpheson L, Adams MR, Anderson WA, Cole MB: Biphasic thermal inactivation kinetics in *Salmonella enteritidis* PT4. Appl. Environ. Microbiol. 1998, *64,* 459-464.
Humphrey TJ: The effects of pH and levels of organic matter on the death rates of salmonellas in chicken scald-tank water. J. Appl. Bacteriol. 1981, *51,* 27-39.
Humphrey TJ: Heat resistance in *Salmonella enteritidis* phage type 4: the influence of storage temperatures before heating. J. Appl. Bacteriol. 1990, *69,* 493-497.
Humphrey TJ, Chapman PA, Rowe B, Gilbert RJ: A comparative study of the heat resistance of salmonellas in homogenized whole egg, egg yolk or albumen. Epidemiol. Infect. 1990, *104,* 237-241.
Humphrey TJ, Cruickshank JG: Antibiotic and deoxycholate resistance in *Campylobacter jejuni* following freezing or heating. J. Appl. Bacteriol. 1985, *59,* 65-71.
Humphrey TJ, Lanning DG: Salmonella and campylobacter contamination of broiler chicken carcasses and scald tank water: the influence of water pH. J. Appl. Bacteriol. 1987, *63,* 21-25.
Humphrey TJ, Lanning DG, Beresford D: The effect of pH adjustment on the microbiology of chicken scald-tank water with particular reference to the death rate of salmonellas. J. Appl. Bacteriol. 1981, *51,* 517-527.
Humphrey TJ, Richardson NP, Gawler AHL, Allen MJ: Heat resistance of *Salmonella enteritidis* PT4: the influence of prior exposure to alkaline conditions. Lett. Appl. Microbiol. 1991, *12,* 258-260.
Humphrey TJ, Richardson NP, Statton KM, Rowbury RJ: Effects of temperature shift on acid and heat tolerance in *Salmonella enteritidis* phage type 4. Appl. Environ. Microbiol. 1993a, *59,* 3120-3122
Humphrey TJ, Slater E, McAlpine K, Rowbury RJ, Gilbert RJ: Salmonella enteritidis phage type 4 isolates more tolerant of heat, acid, or hydrogen peroxide also survive longer on surfaces. Appl. Environ. Microbiol. 1995, *61,* 3161-3164.
Humphrey TJ, Wallis M, Hoad M, Richardson NP, Rowbury RJ: Factors influencing alkali-induced heat resistance in *Salmonella enteritidis* phage type 4. Lett. Appl. Microbiol. 1993b, *16,* 147-149.
Ienistea C, Chitu M, Roman A: Heat resistance in milk of some strains of group D streptococci from pasteurized milk and the influence exerted on their growth by selective media. Zbl. Bakt., I. Abt. Orig. 1970, *215,* 173-181.
Jackson TC, Hardin MD, Acuff GR: Heat resistance of *Escherichia coli* O157:H7 in a nutrient medium and in ground beef patties as influenced by storage and holding temperatures. J. Food Prot. 1996, *59,* 230-237.
Jenkins DE, Schultz JE, Matin A: Starvation-induced cross protection against heat or H_2O_2 challenge in *Escherichia coli.* J. Bacteriol. 1988, *170,* 3910-3914.
Jørgensen F, Panaretou B, Stephens PJ, Knøchel S: Effect of pre- and post-heat shock temperature on the persistence of thermotolerance and heat shock-induced proteins in *Listeria monocytogenes.* J. Appl. Bacteriol. 1996, *80,* 216-224.
Jørgensen F, Stephens PJ, Knøchel S: The effect of osmotic shock and subsequent adaptation on the thermotolerance and cell morphology of *Listeria monocytogenes.* J. Appl. Bacteriol. 1995, *79,* 274-281.
Juneja VK, Foglia TA , Marmer BS: Heat resistance and fatty acid composition of *Listeria monocytogenes:* effect of pH, acidulant, and growth temperature. J. Food Prot. 1998, *61,* 683-687.
Katsui N, Tsuchido T, Takano M, Shibasaki I: Effect of preincubation temperature on the heat resistance of *Escherichia coli* having different fatty acid compositions. J. Gen. Microbiol. 1981, *122,* 357-361.
Katzin LI, Sandholzer LA, Strong ME: Application of the decimal reduction time principle to a study of the resistance of coliform bacteria to pasteurization. J. Bacteriol. 1943, *45,* 265-272.
Kaur J, Ledward DA, Park RWA, Robson RL: Factors affecting the heat resistance of *Escherichia coli* O157:H7. Lett. Appl. Microbiol. 1998, *26,* 325-330.
Kearns AM, Freeman R, Lightfoot NF: Nosocomial

enterococci: resistance to heat and sodium hypochlorite. J. Hosp. Infect. 1995, *30,* 193-199.

Knabel SJ, Walker HW, Hartman PA, Mendonca AF: Effects of growth temperature and strictly anaerobic recovery on the survival of *Listeria monocytogenes* during pasteurization. Appl. Environ. Microbiol. 1990, *56,* 370-376.

Knight KP, Bartlett FM, McKellar RC, Harris LJ: Nisin reduces the thermal resistance of *Listeria monocytogenes* Scott A in liquid whole egg. J. Food Prot. 1999, *62,* 999-1003.

Konvincic I, Mrdjen M, Komnenov-Pupovac V, Vujicic IF, Vulic M, Svabic-Vlahovic M, Tierney JT: Heat resistance of *Listeria monocytogenes* in naturally infected and inoculated cow´s milk. Acta Microbiol. Hung. 1991, *38,* 3-6.

Kornacki JL, Marth EH: Thermal inactivation of *Enterococcus faecium* in retentates from ultrafiltered milk. Milchwissenschaft 1992, *47,* 764-769.

Krishna Iyengar MK, Laxminarayana H, Iya KK: Studies on the heat-resistance of some streptococci. Indian J. Dairy Sci. 1957, *10,* 90-99.

Lategan PM, Vaughn RH: The influence of chemical additives on the heat resistance of *Salmonella typhimurium* in liquid whole egg. J. Food Sci. 1964, *29,* 339-344.

Lemaire V, Cerf O, Audurier A: Thermal resistance of *Listeria monocytogenes.* Ann. Rech. Vét. 1989, *20,* 493-500.

Lemcke RM, White HR: The heat resistance of *Escherichia coli* cells from cultures of different ages. J. Appl. Bacteriol. 1959, *22,* 193-201.

Leyer GJ, Johnson EA: Acid adaptation induces cross-protection against environmental stresses in *Salmonella typhimurium.* Appl. Environ. Microbiol. 1993, *59,* 1842-1847.

Linton RH, Pierson MD, Bishop JR: Increase in heat resistance of *Listeria monocytogenes* Scott A by sublethal heat shock. J. Food Prot. 1990, *53,* 924-927.

Lou Y, Yousef AE: Resistance of *Listeria monocytogenes* to heat after adaptation to environmental stresses. J. Food Prot. 1996, *59,* 465-471.

Lovett J, Bradshaw JG, Peeler JT: Thermal inactivation of *Yersinia enterocolitica* in milk. Appl. Environ. Microbiol. 1982, *44,* 517-519.

Mackey BM, Bratchell N: A review. The heat resistance of *Listeria minocytogenes.* Lett. Appl. Microbiol. 1989, *9,* 89-94.

Mackey BM, Derrick CM: Elevation of the heat resistance of *Salmonella typhimurium* by sublethal heat shock. J. Appl. Bacteriol. 1986, *61,* 389-393.

Mackey BM, Derrick CM: Changes in the heat resistance of *Salmonella typhimurium* during heating at rising temperatures. Lett. Appl. Microbiol. 1987a, *4,* 13-16.

Mackey BM, Derrick CM: The effect of prior heat shock on the thermoresistance of *Salmonella thompson* in foods. Lett. Appl. Microbiol. 1987b, *5,* 115-118.

Mackey BM, Derrick C: Heat shock protein synthesis and thermotolerance in *Salmonella typhimurium.* J. Appl. Bacteriol. 1990, *69,* 373-383.

Mackey BM, Pritchet C, Norris A, Mead GC: Heat resistance of *Listeria:* strain differences and effects of meat type and curing salts. Lett. Appl. Microbiol. 1990, *10,* 251-255.

Magnus CA, Ingledew WM, McCurdy AR: Thermal resistance of streptococci isolated from pasteurized ham. Can. Inst. Food Sci. Technol. J. 1986, *19,* 62-67.

Magnus CA, McCurdy AR, Ingledew WM: Evaluation of four media for recovery of heat-stressed streptococci. J. Food Prot. 1988, *51,* 895-897.

McKenna RT, Patel SV, Cirigliano MC: Thermal resistance of *Listeria monocytogenes* in raw liquid egg yolk. J. Food Prot. 1991, *54,* 816.

Meyer DH, Donnelly CW: Effect of incubation temperature on repair of heat-injured *Listeria* in milk. J. Food Prot. 1992, *55,* 579-582.

Michalski CB, Brackett RE, Hung Y-C, Ezeike GOI: Use of capillary tubes and plate heat exchanger to validate U.S. Department of Agriculture pasteurization protocols for elimination of *Salmonella enteritidis* from liquid egg products. J. Food Prot. 1999, *62,* 112-117.

Moats WA, Dabbah R, Edwards VM: Survival of *Salmonella anatum* heated in various media. Appl. Microbiol. 1971, *21,* 476-481.

Morgan JN, Lin FJ, Eitenmiller RR, Barnhart HM, Toledo RT: Thermal destruction of *Escherichia coli* and *Klebsiella pneumoniae* in human milk. J. Food Prot. 1988, *51,* 132-136.

Mulak V, Tailliez R, Eb P, Becel P: Heat resistance of bacteria isolated from preparations based on seafood products. J. Food Prot. 1995, *58,* 49-53.

Murano EA, Pierson MD: Effect of heat shock and growth atmosphere on the heat resistance of *Escherichia coli* O157:H7. J. Food Prot. 1992, *55,* 171-175.

Murano EA, Pierson MD: Effect of heat shock and incubation atmosphere on injury and recovery of *Escherichia coli* O157:H7. J. Food Prot. 1993, *56,* 568-572.

Muriana PM, Hou H, Singh RK: A flow-injection system for studying heat inactivation of *Listeria monocytogenes* and *Salmonella enteritidis* in liquid whole egg. J. Food Prot. 1996, *59,* 121-126.

Ng H: Heat sensitivity of 300 *Salmonella* isolates. In: U.S. Department of Agriculture, Agricultural Research Service ARS 74-37, 1966, pp. 39-41.

Ng H, Bayne HG, Garibaldi JA: Heat resistance of *Salmonella:* the uniqueness of *Salmonella senftenberg* 775W. Appl. Microbiol. 1969, *17,* 78-82.

Norberg P: Yersinia i opastöriserad mjölk (*Yersinia enterocolitica* in raw milk). Vår Föda 1981, *33,* 45-51 (In Swedish, summary in English).

Northolt MD, Beckers HJ, Vecht U, Toepoel L, Soentoro PSS, Wisselink HJ: Listeria monocytogenes: heat resistance and behaviour during storage of milk and whey and making of Dutch types of cheese. Neth. Milk Dairy J. 1988, *42,* 207-219.

Okrend AJ, Johnston RW, Moran AB: Effect of acetic acid on the death rates at 52°C of *Salmonella newport, Salmonella typhimurium* and *Campylobacter jejuni* in poultry scald water. J. Food Prot. 1986, *49,* 500-503.

Oosterom J, de Wilde GJA, de Boer E, de Blaauw LH, Karman H: Survival of *Campylobacter jejuni* during poultry processing and pig slaughtering. J. Food Prot. 1983, *46,* 702-706, 709.

Osborne WW, Straka RP, Lineweaver H: Heat resistance of strains of *Salmonella* in liquid whole egg, egg yolk, and egg white. Food Res. 1954, *19,* 451-463.

Pagán R, Mañas P, Alvarez I, Sala FJ: Heat resistance in different heating media of *Listeria monocytogenes* ATCC 15313 grown at different temperatures. J. Food Safety 1998, *18,* 205-219.

Pagán R, Mañas P, Raso J, Trepat FJS: Heat resistance of *Yersinia enterocolitica* grown at different temperatures and heated in different media. Int. J. Food Microbiol. 1999, *47,* 59-66.

Palumbo MS, Beers SM, Bhaduri S, Palumbo SA: Thermal resistance of *Salmonella* spp. and *Listeria monocytogenes* in liquid egg yolk and egg yolk products. J. Food Prot. 1995, *58,* 960-966.

Palumbo MS, Beers SM, Bhaduri S, Palumbo SA: Thermal resistance of *Listeria monocytogenes* and *Salmonella* spp. in liquid egg white. J. Food Prot. 1996, *59,* 1182-1186.

Patchett RA, Watson N, Fernandez PS, Kroll RG: The effect of temperature and growth rate on the susceptibility of *Listeria monocytogenes* to environmental stress conditions. Lett. Appl. Microbiol. 1996, *22,* 121-124.

Patel SS, Wilbey RA: Thermal inactivation of γ-glutamyltranspeptidase and *Enterococcus faecium in* milk-based systems. J. Dairy Res. 1994, *61,* 263-270.

Pflug IJ, Holcomb RG: Principles of thermal destruction of microorganisms. In: Block SS (ed.): Disinfection, Sterilization, and Preservation, 3rd edn. Lea & Febiger, Philadelphia, 1983, pp. 751-810.

Quintavalla S, Barbuti S: Resistenza termica di *Listeria innocua* e di *Listeria monocytogenes* isolate da carne suina (Heat resistance of *Listeria innocua* and *Listeria monocytogenes* isolated from pork). Industria Conserve 1989, *64,* 8-12 (In Italian, summary in English).

Quintavalla S, Campanini M: Effect of rising temperature on the heat resistance of *Listeria monocytogenes* in meat emulsion. Lett. Appl. Microbiol. 1991, *12,* 184-187.

Quintavalla S, Campanini M, Miglioli L: Effetto della velocità di riscaldamento sulla resistenza termica di *Streptococcus faecium* (Effect of heating rate on the heat resistance of *Streptococcus faecium*). Industria Conserve 1988, *63,* 252-256 (In Italian, summary in English).

Read RBJr, Bradshaw JG, Dickerson RWJr, Peeler JT: Thermal resistance of salmonellae isolated from dry milk. Appl. Microbiol. 1968, *16,* 998-1001.

Read RBJr, Norcross NL, Hankinson DJ, Litsky W: Come-up time method of milk pasteurization. III. Bacteriological studies. J. Dairy Sci. 1957, *40,* 28-36.

Read RBJr, Schwartz C, Litsky W: Studies on thermal destruction of *Escherichia coli* in milk and milk products. J. Appl. Microbiol. 1961, *9,* 415-418.

Renner P, Peters J: Resistance of enterococci to heat and chemical agents. Zbl. Hyg. Umweltmed. 1998/99, *202,* 41-50.

Richards T, White HRB: The heat disinfection of *Streptococcus faecalis.* Proc. Soc. Appl. Bacteriol. vol. 2, 1949, pp. 61-65.

Rossebø L: Undersøkelser over resistens overfor fuktig varme hos stammer av *Salmonella senftenberg* isolert fra sildemel (Wet heat resistance in strains of *Salmonella senftenberg* isolated from herring meal). Nord. Vet.-Med. 1970, *22,* 631-633 (In Norwegian, summary in English).

Rowan NJ, Anderson JG: Effects of above-optimum growth temperature and cell morphology on thermotolerance of *Listeria monocytogenes* cells suspended in bovine milk. Appl. Environ. Microbiol. 1998, *64,* 2065-2071.

Sanz Pérez B, López Lorenzo P, García ML, Hernández PE, Ordoñez JA: Heat resistance of enterococci. Milchwissenschaft 1982, *37,* 724-726.

Schuman JD, Sheldon BW: Thermal resistance of *Salmonella* spp. and *Listeria monocytogenes* in liquid egg yolk and egg white. J. Food Prot. 1997, *60,* 634-638.

Semanchek JJ, Golden DA: Influence of growth temperature on inactivation and injury of *Escherichia coli* O157:H7 by heat, acid, and freezing. J. Food Prot. 1998, *61,* 395-401.

Shah DB, Bradshaw JG, Peeler JT: Thermal resistance of egg-associated epidemic strains of *Salmonella enteritidis.* J. Food Sci. 1991, *56,* 391-393.

Shannon EL, Reinbold GW, Clark WSJr: Heat resistance of enterococci. J. Milk Food Technol. 1970, *33,* 192-196.

Shenoy K, Murano EA: Effect of heat shock on the thermotolerance and protein composition of *Yersinia enterocolitica* in brain heart infusion broth and ground pork. J. Food Prot. 1996, *59,* 360-364.

Simpson MV, Smith JP, Ramaswamy HS, Simpson BK, Ghazala S: Thermal resistance of *Streptococcus faecium* as influenced by pH and salt. Food Res. Int. 1994, *27,* 349-353.

Solowey M, Sutton RR, Calesnick EJ: Heat resistance of *Salmonella* organisms isolated from spray-dried whole-egg powder. Food Technol. 1948, *2,* 9-14.

Sörqvist S: Heat resistance of *Campylobacter* and *Yersinia* strains by three methods. J. Appl. Bacteriol. 1989, *67,* 543-549.

Sörqvist S: Heat resistance of *Listeria monocytogenes* by two recovery media used with and without cold preincubation. J. Appl. Bacteriol. 1993, *74,* 428-432.

Sörqvist S: Heat resistance of different serovars of *Listeria monocytogenes.* J. Appl. Bacteriol. 1994, *76,* 383-388.

Sörqvist S, Danielsson-Tham M-L: Survival of *Campylobacter, Salmonella* and *Yersinia* spp. in scalding water used at pig slaughter. Fleischwirtsch. 1990, *70,* 1451-1454.

Steinmeyer S: Untersuchungen zu Pathogenität, Hitzeresistenz und Acriflavinempfindlichkeit von Listerienstämmen (Investigations of pathogenicity, heat resistance and acriflavine sensitivity of *Listeria* strains). Dissertation, Munich, 1988, pp. 60-75 (In German).

Stephens PJ, Cole MB, Jones MV: Effect of heating rate on the thermal inactivation of *Listeria monocytogenes.* J. Appl. Bacteriol. 1994, *77,* 702-708.

Stringer SC, George SM, Peck MW: Thermal inactivation of *Escherichia coli* O157:H7. J. Appl. Microbiol. Symposium Supplement 2000, *88,* 79S-89S.

Stumbo CR: Thermobacteriology in Food Processing, 2nd edn. Academic Press, New York, 1973, pp. 70-120.

Suárez Fernández G, Suárez Rodríguez M, Fernández Garayzabal F, Domínguez Rodríguez L: Termorresistencia de *Listeria monocytogenes* (Thermal resistance of *Listeria monocytogenes*). Alimentaria 1989, *200,* 51-53 (In Spanish, summary in English).

Teo Y-L, Raynor TJ, Ellajosyula KR, Knabel SJ: Synergistic effect of high temperature and high pH on the destruction of *Salmonella enteritidis* and *Escherichia coli* O157:H7. J. Food Prot. 1996, *59,* 1023-1030.

Thomas CT, White JC, Longrée K: Thermal resistance of salmonellae and staphylococci in foods. Appl. Microbiol. 1966, *14,* 815-820.

Thompson WS, Busta FF, Thompson DR, Allen CE: Inactivation of salmonellae in autoclaved ground beef exposed to constantly rising temperatures. J. Food Prot. 1979, *42,* 410-415.

Toora S, Budu-Amoako E, Ablett RF, Smith J: Effect of high-temperature short-time pasteurization, freezing and thawing and constant freezing, on the survival of *Yersinia enterocolitica* in milk. J. Food Prot. 1992, *55,* 803-805.

Tsuchido T, Takano M, Shibasaki I: Effect of temperature-elevating process on the subsequent isothermal death of *Escherichia coli* K-12. J. Ferment. Technol. 1974, *52,* 788-792.

Vrchlabsky J, Leistner L: Hitzeresistenz der Enterokokken bei unterschiedlichen a_w-Werten. (Heat resistance of enterococci at different a_w values). Fleischwirtsch. 1970, *50,* 1237-1238. (In German, summary in English).

Waterman SC: The heat-sensitivity of *Campylobacter jejuni* in milk. J. Hyg., Camb. 1982, *88,* 529-533.

White HR: The heat resistance of *Streptococcus faecalis.* J. Gen. Microbiol. 1953, *8,* 27-37.

White HR: The effect of variation in pH on the heat resistance of cultures of *Streptococcus faecalis.* J.

Appl. Bacteriol. 1963, *26,* 91-99.
Williams NC, Ingham SC: Changes in heat resistance of *Escherichia coli* O157:H7 following heat shock. J. Food Prot. 1997, *60,* 1128-1131.
Williams NC, Ingham SC: Thermotolerance of *Escherichia coli* O157:H7 ATCC 43894, *Escherichia coli* B, and an *rpoS*-deficient mutant of *Escherichia coli* O157:H7 ATCC 43895 following exposure to 1.5% acetic acid. J. Food Prot. 1998, *61,* 1184-1186.
Wolfson LM, Sumner SS: Antibacterial activity of the lactoperoxidase system against *Salmonella typhimurium* in trypticase soy broth in the presence and absence of a heat treatment. J. Food Prot. 1994, *57,* 365-368.
Xavier IJ, Ingham S: Increased D-values for *Salmonella enteritidis* resulting from the use of anaerobic enumeration methods. Food Microbiol. 1993, *10,* 223-228.
Yamamori T, Yura T: Genetic control of heat-shock protein synthesis and its bearing on growth and thermal resistance in *Escherichia coli* K-12. Proc. Natl. Acad. Sci. USA 1982, *79,* 860-864.
Zivanovic R, Oluski A, Tadic Z: Contribution to the knowledge of thermoresistance of the group D streptococci by Lancefield. Tehnologija Mesa 1965, *6,* 198-205.

Sammanfattning

Värmeresistens i vätskor hos Enterococcus-, Listeria-, Escherichia-, Yersinia- , Salmonella- and Campylobacter-arter.

Syftet med arbetet var att samla in, utvärdera, sammanfatta och jämföra värmeresistensdata som rapporterats för *Campylobacter, Enterococcus, Escherichia, Listeria, Salmonella* and *Yersinia* spp. Resultat erhållna under så likartade experimentella förhållanden som möjligt eftersträvades. Noterade värmeresistensvärden, $\log_{10}$ *D*-värden, och rapporterade behandlingstemperaturer användes för upprättande av temperatur-avdödningslinjer för de olika bakteriegrupperna (*D*-värdet är den tid som krävs vid en viss behandlingstemperatur för att 90% av bakterierna skall inaktiveras). Med användning av lutningen hos respektive linje och lutningens 95%-konfidensintervall beräknades *z*-värdet och dess 95%-konfidensgränser (*z*-värdet är den temperaturändring som erfordras för att *D*-värdet skall öka eller minska med en 10-potens). Beräknade *z*-värden jämfördes med *z*-värden som erhållits från litteraturen. Linjernas ekvationer användes också för uträkning av *D*-värdesmedeltal och dessas 95%-konfidensgränser vid olika behandlingstemperaturer. 95%-konfidensgränser för "predicted" ("förutspådda") individuella *D*-värden räknades också ut. Linjer och värden visas i figurer och tabeller. Vissa noterade skillnader i värmeresistens mellan och inom bakteriegrupperna diskuteras i artikeln.

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